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Rapid, absolute calibration of x-ray filters employed by laser-produced plasma diagnostics[a)]

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The Electron Beam Ion Trap (EBIT) facility at the Lawrence Livermore National Laboratory is being used to absolutely calibrate the transmission efficiency of x-ray filters employed by diodes and spectrometers used to diagnose laser-produced plasmas. EBIT emits strong, discrete monoenergetic lines at appropriately chosen x-ray energies. X rays are detected using the high resolution EBIT Calorimeter Spectrometer (ECS), developed for LLNL at the NASA/Goddard Space Flight Center. X-ray filter transmission efficiency is determined by dividing the x-ray counts detected when the filter is in the line of sight by those detected when out of the line of sight. Verification of filter thickness can be completed in only a few hours, and absolute efficiencies can be calibrated in a single day over a broad range from about 0.1 to 15 keV. The EBIT calibration lab has been used to field diagnostics (e.g., the OZSPEC instrument) with fully calibrated x-ray filters at the OMEGA laser. Extensions to use the capability for calibrating filter transmission for the DANTE instrument on the National Ignition Facility are discussed. © *2008 American Institute of Physics.*
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I. INTRODUCTION

Thin filters made of pure metals or metal-coated plastic serve many purposes in diagnostics used to study both laboratory and celestial plasmas. They have been used to filter out optical radiation from light-sensitive x-ray charge coupled device cameras and multichannel plates, filter out thermal and far UV radiation from x-ray microcalorimeters, used as debris shields, and to provide energy fiducials created by absorption edges for *in situ* energy calibration. The x-ray transmission of these filters is energy dependent. Hence, proper interpretation of spectra that pass through a filter requires accurate knowledge of the filter's transmission efficiency as a function of energy.

Assuming the filter material acts like a collection of noninteracting atoms, its x-ray transmission efficiency can be described by

$$T = e^{-n\mu d}, \tag{1}$$

where n is the number of atoms per unit volume, μ is the energy dependent atomic photabsorption cross section, and d is the thickness of the material. Photoabsorption cross sections derived from semiempirical atomic scattering factors have been tabulated by the Center for x-ray Optics[1] (www-cxro.lbl.gov) and in most cases are highly reliable. Therefore, if the thickness and density of a material are known, Eq. (1) can be used to reliably predict the x-ray transmission in energy bands away from absorption edges. Near absorption edges, however, Eq. (1) is no longer valid because the assumption of a collection of noninteracting atoms breaks down and the chemical state of the material must be taken into account.

Because most diagnostics require high throughput, they employ the thinnest possible filters, i.e., on the order of 0.1–2 μm. For these thicknesses, the uncertainties provided by the manufacturer is ~10% at best, and often worse. Additional uncertainties in the density of complex materials may also be present. A 10% uncertainty in the product $d \cdot n$ translates to an uncertainty of up to 4% in the transmission depending on if the incident photon energy is near an absorption edge. Because of these uncertainties and the fact that some experiments require transmission to be known to better than 4%, the x-ray transmission of a diagnostic's blocking filter must be measured.

X-ray transmission is often measured using large synchrotron sources such as the National Synchrotron Light Source at Brookhaven National Laboratory or the Advanced Light Source at Lawrence Berkeley National Laboratory. Standard x-ray tubes coupled with high resolution grating spectrometers, such as the facility found at NASA/Goddard Space Flight Center,[2] have also been used. In the case of the synchrotron sources, the actual calibration of a filter may be completed in only a few hours; however, beam time availability and the logistics of setting up the experiment require turn around times on the order of several weeks or months. In addition, these facilities only have standard arrangements to measure transmission at energies below 6 keV. In the case

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of an x-ray tube coupled to a high resolution spectrometer, the time required to measure a single filter is several weeks or longer because it is necessary to use relatively weak bremsstrahlung radiation and also because covering a spectrometer's full range may require several settings.

We have developed a novel facility for rapid, absolute calibration of the x-ray transmission efficiency of thin blocking filters, specifically to calibrate filters used by diagnostics of laser-produced plasmas. This facility is located at the Lawrence Livermore National Laboratory and is centered around the EBIT Calorimeter Spectrometer (ECS), built by the Calorimeter Group at the NASA/Goddard Space Flight Center, and LLNL's Electron Beam Ion Trap (EBIT). Using this facility, filters can be fully calibrated in approximately one day across an instrument's entire operating band. In addition, because the facility is located at LLNL, filters used in NIF experiments or as part of Omega campaigns can be fully calibrated immediately before or after the experiments are completed with no long wait for beam time availability. Here, we present a description of the experimental arrangement and a measurement of the transmission of a filter employed by a grating spectrometer used to diagnose plasmas produced by the Omega laser facility.

II. EXPERIMENTAL ARRANGEMENT

Direct measurement of a filter's transmission efficiency requires an x-ray source, an x-ray spectrometer, and method for comparing radiation incident on the filter to the radiation that passes through. Our method uses the LLNL EBIT as an x-ray source and the ECS for the spectrometer. Radiation incident on the filter is compared to radiation that passes through the detector by measuring the spectrum produced by EBIT with the ECS with and without the filter in the spectrometer's line of sight. Simultaneously, the x-ray flux from EBIT is monitored independently by spectrometers during both the filter-in and filter-out measurements. By dividing the "in" measurement by the "out" measurement, the absolute filter efficiency is determined.

The LLNL EBIT produces strong, discrete line radiation by ionizing, trapping, and exciting highly charged ions. A detailed description of the LLNL EBIT can be found elsewhere.[3,4] LLNL's EBIT facility has been used to create almost any charge state of any ion up to U^{92+}. Hence, producing line radiation in the energy band for a specific diagnostic can be achieved easily by introducing the appropriate element into the trap.

The ECS is used to detect photons for both the in and the out measurements. It is a microcalorimeter instrument built for the EBIT facility by the x-ray Calorimeter Group at the NASA/Goddard Space Flight Center.[5,6] It consists of an array of 32 microcalorimeter channels that cover an energy range of 100 eV up to and beyond 60 keV. The array has 18 channels optimized for energies between 0.1 and 15 keV, and 14 channels optimized for high energy. The low energy channels have an energy resolution of 5–10 eV, and the high energy channels have a resolution of $\sim$35 eV. Because the ECS's energy coverage is broadband, large sections or all of a diagnostic's bandwidth can be calibrated at once.

Filters are translated in and out of the x-ray beam line using a vacuum feed through translation system. The system consists of a filter mounting plate that has three equal size open holes, which allow x-rays to pass through, and a translation arm for moving the filters in and out of the x-ray beam. The holes are cut to the same size to ensure that the detector samples the same portion of the trap region for both the in and out measurements. For a measurement, one or two filters are placed on the mounting plate, covering one or two of the holes, one filter per hole. This makes it possible to calibrate two filters without breaking vacuum. The mounting plate is then placed on the translation arm and inserted in the vacuum chamber between EBIT and the ECS.

To normalize the x-ray emission from EBIT between the in and out measurements, either one or several independent x-ray spectrometers are used to monitor EBIT's x-ray emission. Many spectrometers are available for this task, including high purity germanium solid state detectors, high resolution grazing incidence spectrometers,[7,8] and high resolution crystal spectrometers.[9,10] Depending on the particular x-ray energy being used, one or several of these may be in operation during a measurement.

III. MEASUREMENT

We have used the calibration facility at LLNL to measure several filters already fielded in spectrometers used at the Omega laser, i.e., the Ozspec crystal spectrometer[11] and the variable spaced grating (VSG) spectrometer. Here we present the measurement of the VSG filter.

The filter used in the VSG is a freestanding 1.75×1.75 in.^{2} aluminized lexan filter made by the Luxel corporation. This is a standard-size filter employed by x-ray framing cameras used by many diagnostics at Omega. The thicknesses quoted by Luxel for this filter are 0.2 μm of lexan and 0.15 μm of aluminum.

The filter was calibrated across the 200–2000 eV energy band, i.e., the bandwidth of interest to the VSG spectrometer and also the range where the filter has the most dynamic response. To cover this band, we used x-ray lines from *K*-shell transitions in hydrogenic and heliumlike carbon, nitrogen, oxygen, and neon, from *L*-shell transitions in neonlike krypton, and from the continuum across the carbon edge. Carbon and oxygen were injected as CO_2, and nitrogen is a background gas present in the EBIT vacuum chamber during this experiment. Line emission from all three elements was measured simultaneously. As an example, the in and out spectra used to generate the data points below 900 eV are given in Fig. 1. Neon and krypton were injected independently as neutral gas and spectra from those elements was collected separately. 1 h for each in and out spectra for CO_2, Ne, and Kr were taken, for a total time of 6 h.

Figure 2 shows the results of the measured transmission compared to the theoretical curve for the quoted thickness of the lexan and aluminum calculated using the tools at the Center for x-ray Optics website. The errors for each measured data point include the statistical error and an estimate of the systematic error. Our measurement agrees fairly well with the calculated transmission based on the quoted thick-

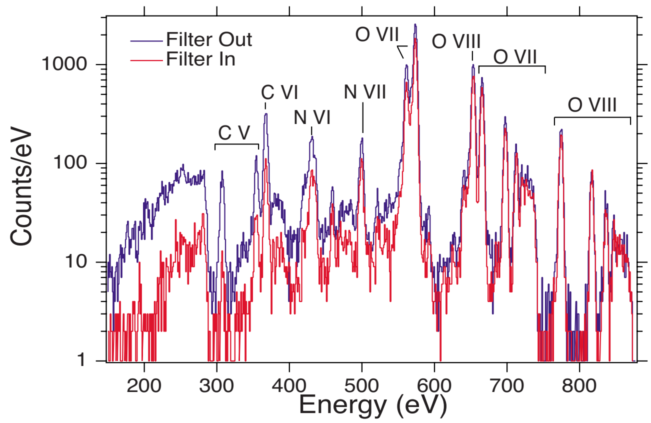

FIG. 1. (Color online) Comparison of spectra measured with the VSG filter in and filter out in the 150–900 eV energy band measured with the ECS.

ness of the filters. Above the aluminum edge at ~1560 eV, the measured transmission is about 4% higher than predicted. This may indicate that the filter contains more lexan and less aluminum than quoted; however, if less aluminum is present, the transmission curve falls well outside the errors of the data points below the carbon edge, even with additional lexan. We note that the data points at 837 and 1210 eV are 18% and 6% below the prediction, respectively, and do not agree within the measurement errors. We also note that for some filters that were measured (not those manufactured by Luxel) thicknesses that were greater than a factor of 5 larger than quoted were found. These differences emphasize the fact that accurate knowledge of filter's x-ray transmission cannot be based on the thickness quoted by the manufacturer; the transmission must be measured.

Using EBIT-ECS calibration facility, the x-ray transmission of thin filters can be measured with quick turn around times and to an accuracy level of 3% in the energy range between 0.1 and 2 keV, better than the 5% accuracy required by NIF's Dante instrument for filters in this band. The fast turn around times and proximity to the NIF facility make it possible to calibrate filters used in NIF within one day of an experiment. This is especially important for instruments where filters may change their properties from shot to shot. In addition, this facility makes it possible to field diagnostic spectrometers at the Omega laser facility, such as the OZSPEC,[11] the VSG, and the Mspec,[12] with fully calibrated filters. The EBIT-ECS calibration facility can calibrate filters up to 15 keV, well beyond the standard 6 keV provided by the Brookhaven facility or the ALS at LBNL. Future upgrades to our system include the ability to provide transmission measurements as a function of position and also implementing an automatic filter-translation, spectra- acquisition system. Position information is especially important for diagnostics employing crystals or gratings because photons of different energies pass through the filter at different locations. The development of this facility is especially timely given the fact that the calibration facility at Brookhaven National Laboratory usually used for filter calibration will have shortened operation periods or will be shut down at various times over the next few years because of upgrades to the synchrotron.

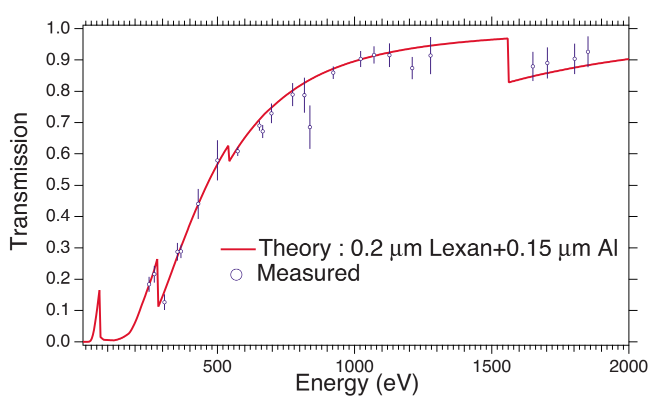

FIG. 2. (Color online) Transmission of a blocking filter manufactured by the Luxel corporation. All the data points on were acquired in a total of 6 h.

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